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A DIRECT-CURRENT TRANSFORMER

by

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SUMMARY

This is a simple description of a new device which may properly be called a direct-current transformer. The direct-current transformer is only operative at superconducting temperatures. It is constructed of thin superconducting films, and to understand why and how it works, the properties of both Type I and Type II superconductors are briefly discussed.

KEY WORDS superconductor, transformer, electronics

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A DIRECT-CURRENT TRANSFORMER

I. Giaever

INTRODUCTION

Ordinary transformers operate on an alternating current, and the concept of a transformer that can operate on a direct current has often been mentioned as a joke by electrical engineers. However, it is possible to construct a device that may be called a d-c transformer by utilizing the unique magnetic and electrical properties of some superconductors. In fact, it is possible to construct two entirely different kinds of d-c transformers with superconductors. By simply winding the secondary coil in an ordinary transformer with superconducting wire and using only a superconducting load, we can, in a sense, create a d-c transformer. The current in the secondary circuit will always follow the current in the primary circuit--even when the primary current is a direct current. This follows directly from the fact that a superconductor has zero resistance below the superconducting transition temperature. However, as soon as we attempt to take power out of the secondary circuit; for example, by loading it with a resistor, it ceases to work on direct currents. Therefore, this device can be considered a d-c transformer only in a trivial sense.

In this report I shall describe a newly constructed type of d-c transformer in which it is possible to transform a direct current or voltage, and where it is also possible to extract power from the secondary circuit. To understand how this transformer operates, it is necessary to review some of the unique properties of superconductors.

TYPE I SUPERCONDUCTORS

It is common to distinguish between two different types of superconductors, referred to as type I and type II. A type I superconductor is the "classical" superconductor which is characterized by a zero resistance and by the fact that the magnetic field inside the superconductor itself is always zero.(1) Typical type I superconductors are: Pb, Sn, and In. For example, let us do an experiment with a toroid or doughnut-shaped ring made of tin. First, we place it in a bath of liquid helium, which has a boiling point of 4.2°K. Let us imagine that a small uniform magnetic field is applied parallel to the axis of the toroid as shown in Fig. 1. At 4.2°K, the tin is still in its normal state and the magnetic field will be practically undisturbed by the presence of the ring (Fig. 1A). Now let us slowly cool the assembly down by letting the liquid helium evaporate under a reduced pressure. Tin becomes superconducting at approximately 3.7°K, and if we look at the ring at 3.5°K for example, we will find that the magnetic field has been expelled from the interior of the tin (Fig. 1B). The field is expelled because currents are induced on the surface of the tin to a depth of about $\lambda \sim 500$ Å, called the penetration depth. These currents always flow in such a manner as to make the field inside the superconductor zero.

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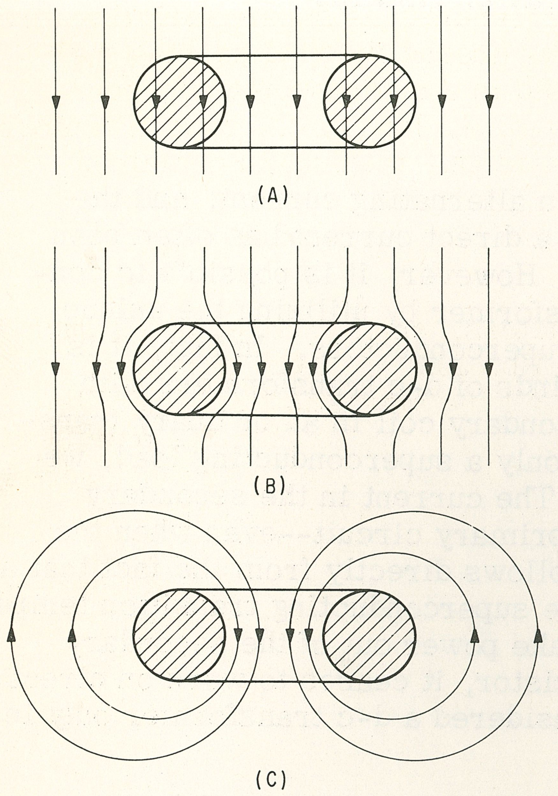

Fig.1 (A) A toroid shaped ring of tin in a small magnetic field. The tin is in the normal state; (B) the toroid in the superconducting state. The magnetic field has been excluded from the interior of the ring; (C) if the applied field is removed, a current is induced in the toroid such that the flux (fluxoid) contained in the hole is kept unchanged.

Another very peculiar phenomenon is that the total currents and total fields always adjust themselves in such a manner that the following integral around any closed contour or loop contained inside a superconductor is satisfied:

$$\int \bar{B}\cdot d\bar{S} + \mu\lambda^2 \oint \bar{j}\cdot d\bar{l} = n\frac{h}{2e} = n\Phi_0 \quad . \qquad (1)$$

The first term equals the amount of flux contained within the chosen closed contour as $\bar{B}$ is the magnetic flux density and $d\bar{S}$ an infinitesimal area element. The second term is the line integral of the current density $\bar{j}$ along the closed contour where $d\bar{l}$ is an infinitesimal line element, λ the penetration depth, and $\mu = 4\pi \times 10^{-7}$ in mks units. n is simply an integer, and $\varphi_0 = h/2e \sim 2 \times 10^{-15}$ Weber is the flux quantum where h is Planck's constant and e is the electronic charge. If the chosen contour is a simply connected structure, i.e., if the interior is superconducting, n = 0. However, if we integrate around a multiply connected structure such as our toroid, n can take on any integral value. Because currents flow only close to the surfaces of type I superconductors, we can almost always choose a contour such that the second term on the left in Eq. (1) is zero. For example, if we integrate along a line in the interior of the toroid close to the center of its cross section, the current is effectively zero, and we talk (loosely) about "flux-quantization," i.e., the flux contained within a macroscopically large superconducting ring is quantized in multiple units of φ_0. Any other path contained within the superconducting ring and that encloses the hole will give exactly the same answer for the sum of the two integrals; however, the second term involving the current is not necessarily zero, and for this reason, London,(2) who first suggested this concept, spoke of the quantization of the "fluxoid", i.e., of the sum of the two integrals.

Now if the external magnetic field surrounding the superconducting toroid is removed, a current will be induced that flows around the ring keeping the fluxoid constant (Fig. 1C). Thus, flux contained in a macroscopic superconductor is not only quantized, it is also conserved. As long as the chosen contour of integration is kept within superconducting material, the fluxoid contained within the contour is conserved.

TYPE II SUPERCONDUCTORS

Let us next look at type II superconductors, which include alloys such as BiPb, PbIn, Nb_3Sn, and also possibly pure Nb. Just as is the case for a type I superconductor, the type II will exclude all the magnetic field from its interior when the applied magnetic field is low. If the applied field is increased (until the so-called critical field is reached), the type I superconductor described above reverts to the normal state through a first-order phase transition. Similarly, in a sufficiently high magnetic field, the type II superconductor also becomes normal; however, there exists an intermediate range of fields where the type II superconductor exists in a never-never land, i.e., in a sense it is neither normal nor superconducting. A schematic magnetization curve is shown in Fig. 2 for both a type I and a type II superconductor.

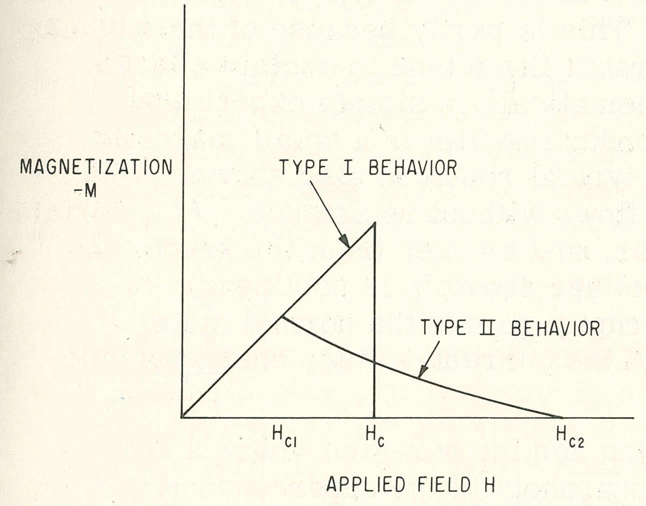

Fig. 2 Magnetization curves for type I and type II superconductors. Since $B = H + M = \mu H$, for a type I superconductor, $\mu = 0$; while for a type II superconductor $\mu \neq 0$ for fields $H_{c1} < H_{c2}$.

In the intermediate field range the flux does indeed penetrate the type II superconductor, but only in certain spots schematically as shown in Fig. 3. It is possible to think of the center of each spot as a core of normal material that is surrounded by circulating current in the superconductor. In a sense, each of the spots looks like the toroid we described above, and the fluxoid of each spot is quantized and conserved. However, now each fluxoid will contain only one flux quantum, i.e., in Eq. (1) n = 1. We shall refer to such a spot as a "fluxon." The magnetic structure is often referred to as the "Abrikosov(3) structure," after the first person who visualized this strange behavior in a superconductor.

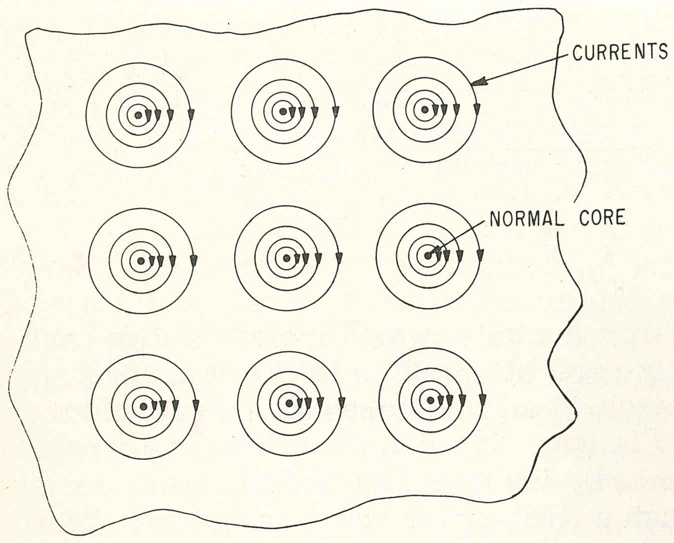

Fig. 3 A type II superconductor in an intermediate homogeneous magnetic field applied perpendicular to the plane of the paper. The magnetic field will penetrate in certain spots, and a current will be induced, which keeps the magnetic field "bundled up." In a very pure type II superconductor, the magnetic field will penetrate in a regular array.

THIN SUPERCONDUCTING FILMS

Since the d-c transformer I shall talk about is constructed from thin superconducting films, let us concentrate on such structures. It turns out that thin, evaporated, superconducting films tend to behave as type II superconductors irrespective of the material they contain. This is partly because of their demagnetization factor and partly because evaporated films tend to contain a large amount of impurities. Figure 4 shows schematically a simple experiment measuring the resistivity of a thin superconducting film in a small magnetic field applied perpendicular to the film. A typical result is also shown. When a small current is passed along the film, it flows without resistance. At a certain current, I_0, however, a voltage will appear, and as seen from the graph, the relationship between the current and the voltage above I_0 is nonlinear. At a current somewhat higher, the film will abruptly go into the normal state, presumably because of heating effects, and the current-voltage characteristic follows Ohm's law.

We shall be concerned only with the nonlinear region where a voltage first appears. If we regard Fig. 4 as a "snapshot" of the superconducting film, it seems strange that a voltage should appear across the film because it is possible to draw an imaginary line across the film without crossing any resistive material. However, we must remember that a voltage in general consists of both a resistive and an inductive term. Since the resistive voltage is zero, the answer must be that flux is cutting our imaginary line such that we obtain an inductive-like voltage. To obtain this result, we let the flux pattern in the film change as a function of time; specifically, the flux pattern will move across the film from one side to the other. Thus, from time to time, the rather arbitrary line we drew across the film will also be crossed by resistive material. This model of a moving flux pattern was first suggested by Anderson.(4) [A similar model had previously been suggested by Gorter(5) for type I superconductors in the intermediate state.] At first sight this model seems very artificial and unphysical, as it literally moves flux across the film from one side to the other.

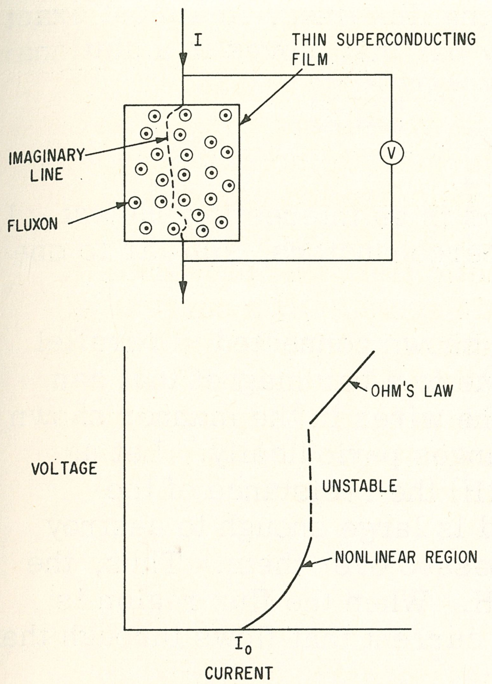

Fig. 4 A simple arrangement for measuring the current-voltage characteristic of a superconducting film placed in a small applied field perpendicular to the paper. At first, the transport current I avoids the normal cores and the current flows without loss. At a current I_0, because of the Lorentz force between the flux spots and the transport current, the flux spots will move across the film causing a voltage to appear. Because the flux spots move, the transport current cannot avoid the normal cores, and in an approximate sense this accounts for the I^2R loss. Finally, at a higher current, the film abruptly enters the normal state and Ohm's law is obeyed.

If we remember that the flux lines have meaning only inside the superconductor, everything works out all right. In Fig. 5 a schematic flux plot of the film is shown with the flux lines in various positions. Since flux lines carry no particular meaning in a uniform field, as can be understood from Fig. 5, the flux pattern within the film may change or move uniformly leaving the magnetic field a little distance away from the film completely unaffected. The force on the flux lines is provided by the transport current flowing in the film.

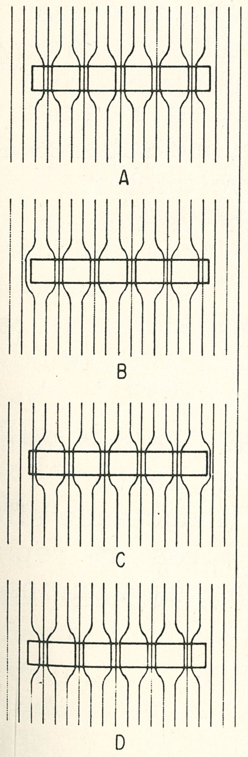

Fig. 5 A schematic flux plot of the cross section of a superconducting film in a uniform field. As seen from the drawing, it is possible to let the flux move within the film without disturbing or changing the field a little distance away from the film. The important fact is that flux lines have no particular significance in a uniform field, while concentration of magnetic field is well defined inside the superconductor.

To sum up, we regard the voltage appearing along a stationary superconductor in the type II state as being caused by moving flux lines, in almost exact analogy to the voltage appearing along an ordinary bar that moves in a stationary magnetic field.

A UNIPOLAR GENERATOR

The motion of flux inside superconductors is an interesting subject. I shall now describe a unipolar generator using superconductors, similar to one proposed by Volger.$^{(6)}$

In Fig. 6 two superconducting wires are shown connected in parallel across a voltmeter. Imagine now a flux region due to a bar magnet that can move parallel to, but spaced from, the plane of the wires in the manner shown such that the magnetic flux threading the loop changes periodically. Let us designate the resistance of the superconductor R(H) the resistance of the voltmeter R_V. We assume that the magnetic field is large enough to destroy superconductivity in the wires when the magnet passes over them. Thus, the resistance R(H) depends upon the magnetic field H. When the flux region is moved across the first superconductor, the total current that flows through that conductor is:

$$I = \frac{\text{emf}}{R(H) + \dfrac{R(0) \cdot R_V}{R(0) + R_V}} = \frac{\text{emf}}{R(H)} , \qquad (2)$$

and the current through the voltmeter is simply:

$$I_V = \frac{R(0)}{R(0) + R(H)} \quad I = 0 , \qquad (3)$$

and finally the voltage registered by the voltmeter is:

$$V = R_V I_V = 0 . \qquad (4)$$

[Since the resistance R(0) = 0, the voltage registered by the voltmeter is zero.] The same argument applies when the flux region crosses the second superconductor because now the first superconductor short circuits the voltmeter. Finally, when the flux region moves out of the loop containing the voltmeter, the current through the voltmeter is:

$$I_V = \frac{\text{emf}}{R_V + \dfrac{R(0) \cdot R(0)}{R(0) + R(0)}} = \frac{\text{emf}}{R_V} , \qquad (5)$$

and therefore the voltage registered is equal to the induced emf. We see then that the voltmeter on the average will register a direct voltage as the two superconducting wires effectively act as a perfect commutator (inductance effects are ignored). A similar effect is produced if the two separate wires are replaced by a flat plate as indicated in Fig. 6, as we may think of the plate as a number of wires placed in parallel.

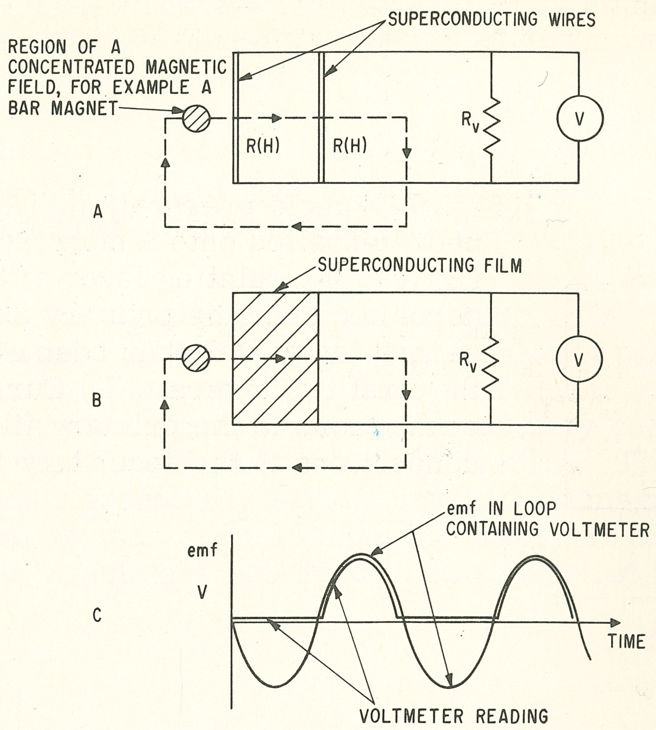
SUPERCONDUCTING WIRES
REGION OF A CONCENTRATED MAGNETIC FIELD, FOR EXAMPLE A BAR MAGNET
R(H)
R(H)
R_V
V
A
SUPERCONDUCTING FILM
R_V
V
B
emf IN LOOP CONTAINING VOLTMETER
emf
V
C
TIME
VOLTMETER READING

Fig. 6 (A) A possible unipolar generator. When the magnetic flux region crosses the first superconducting wire, it goes into the normal state and an emf is also induced. No current flows at this time through the voltmeter as it is effectively short-circuited by the second superconducting wire. When the magnet crosses the second superconducting wire, the first wire short-circuits the voltmeter. Only when the flux region leaves the loop containing the voltmeter is a voltage observed. (B) The superconducting wires have been replaced by a flat superconducting plate. (C) The emf in the loop containing the voltmeter and the voltage registered on the voltmeter as a function of time.

THE DIRECT-CURRENT TRANSFORMER

Now let us consider the construction of a d-c transformer.$^{(7-9)}$ The simplest construction procedure is shown in Fig. 7. First, a tin film a few thousand angstroms thick is evaporated onto a microscope glass slide. I shall refer to this film as the primary. Next, a thin film of silicon oxide approximately 100 to 200 Å thick is evaporated over the primary film to form a thin insulating layer. Finally, a second tin film is evaporated on the top. I shall refer to this film as the secondary. The secondary film is made as thin as possible, i.e., in the order of 500 to 1000 Å, and it is made slightly narrower than the primary film.

The experiment consists of passing a current down the primary film I_p and measuring both the primary voltage V_p and the secondary voltage V_s. Because of the narrow section in the center of the primary film, the voltage drop in the primary is completely paralleled by the secondary (the wide ends remain superconducting). The current and voltage connections are shown in Fig. 7. As illustrated in Fig. 8, as soon as both films are superconducting, a voltage appears in the top film.

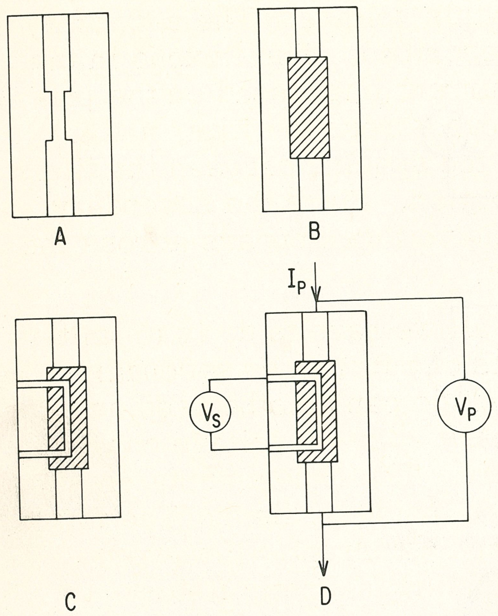

Fig. 7 Sample preparation. (A) A Sn film has been deposited onto a microscope glass slide. (B) A thin insulating layer of SiO is vacuum-deposited over the primary Sn film. (C) A second layer of Sn has been evaporated over the first two layers. (D) Current and voltage connections to the primary film, and voltage connections to the secondary film.

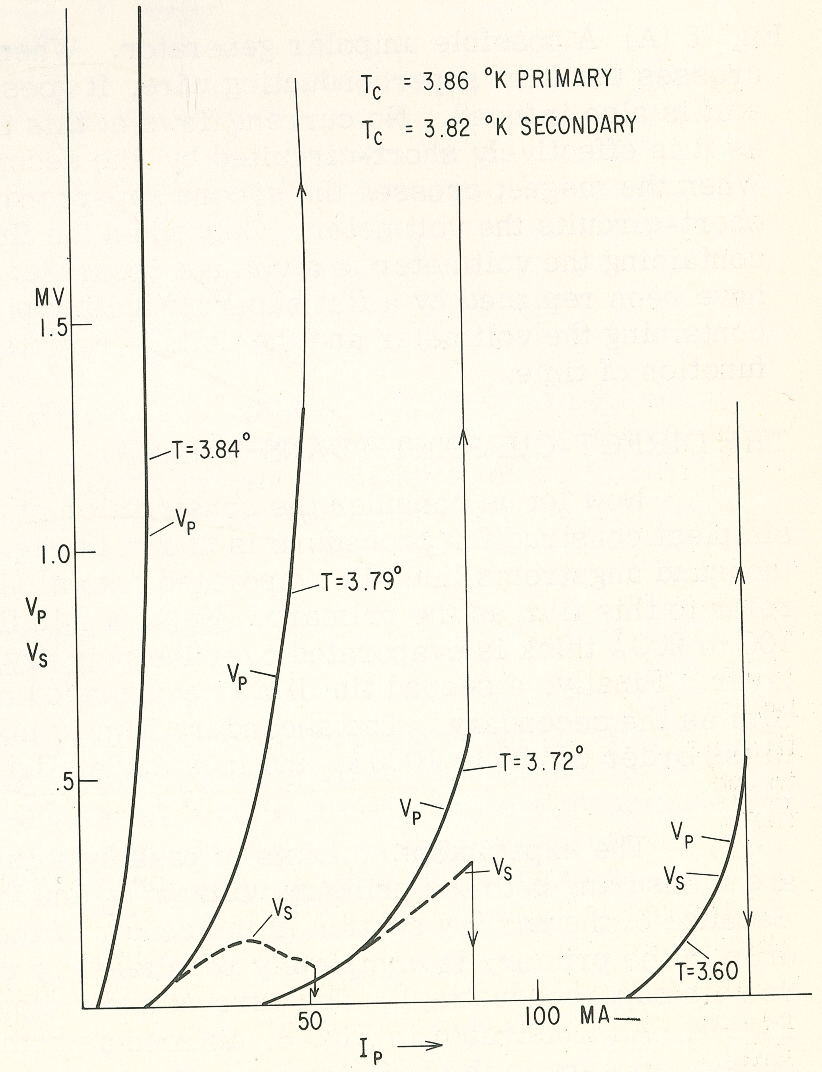

Fig. 8 The primary voltage V_P and the secondary voltage V_S as a function of the primary current I_p at various temperatures. Note that the two films have different superconducting transition temperatures, T_C, and that both films have to be superconducting for the transformer action to take place.

We should now understand the reason for this voltage. The secondary film works similar to the unipolar generator we described. The fluxons in the primary film behave as very small magnets. A current impressed on the primary film will at one point cause the fluxons to move across the film, and a voltage appears along the primary film. Because the spacing between the films is so small, the secondary film senses this flux motion. Since the secondary film acts as a nearly perfect commutator, the same voltage appears across the secondary film.

Now if we want to transform the voltage, all we have to do is to imitate a regular transformer. Figure 9 shows the results of putting two secondary films in series on top of one primary film. The device can also be used as a rectifier as illustrated in Fig. 10, where the primary current-voltage characteristic is plotted as a function of secondary current. The experimental results shown here are taken essentially without any applied magnetic field. The fluxons are caused entirely by the self-field from the transport current. However, basically the same effects are observed in small applied magnetic fields.

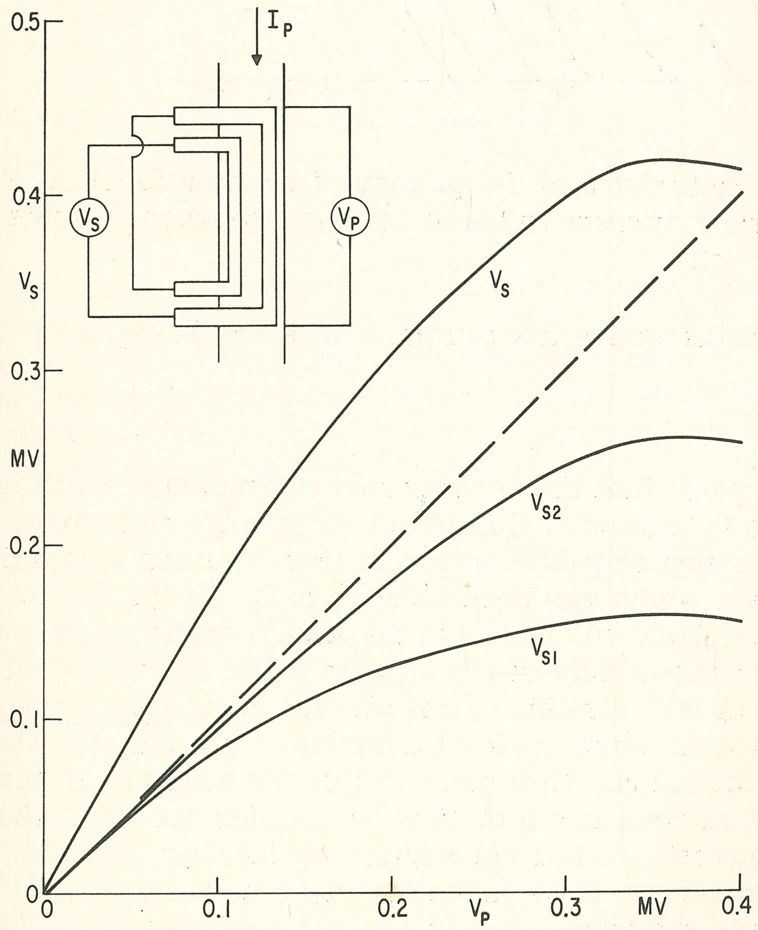

Fig. 9 The experimental arrangements of a transformer with a turn ratio of 2:1. The primary voltage V_p is plotted as a function of the secondary voltage, measured in each secondary film separately, V_{S1} and V_{S2}, and coupled in a series, V_S.

I do not want to leave the impression that this d-c transformer will find great commercial applications. At present, to my knowledge, superconducting electronics are not used commercially, and there are probably not yet sufficient advantages to this new device to induce people to use the liquid helium temperatures that are necessary. However, the device may find its way into

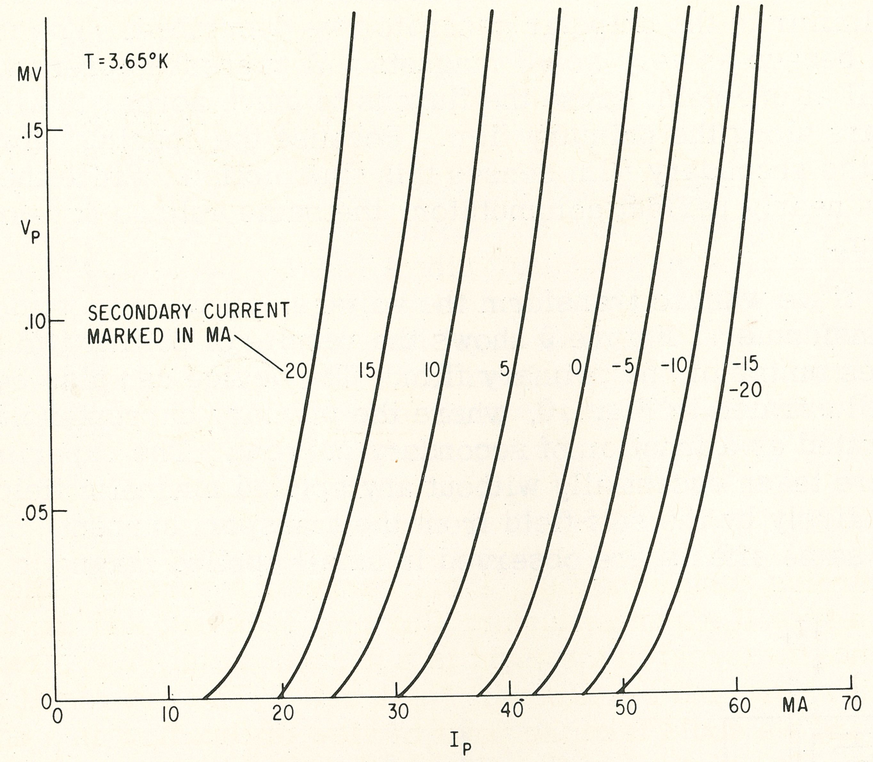

Fig. 10 The current-voltage characteristic of the primary film as a function of secondary current. The secondary current is taken as negative when it flows antiparallel to the primary current.

commercial applications in situations where low temperatures are being used anyhow for other reasons.

FLUX MOTION

Finally, I should like to show that the concept that the measured voltage in a type II superconductor is due to motion of flux is not so strange as it may first seem. In Fig. 10 is shown a superconducting toroid that contains a certain amount of flux because of a current which has been induced in it. If the toroid is made of a type II material, flux lines will leak into the superconductor as shown and annihilate each other in the middle of the section. The net result will be that the flux enclosed in the ring will diminish, and we talk about flux leakage. If, on the other hand, a similar toroid were made of a normal material, the flux enclosed in the ring would again diminish. However, in this case we are inclined to talk about the resistance of the normal section. Yet we can just as well take the point of view that flux leaks across the normal section of the ring, and the two cases can then be treated similarly. If we make the rings very large and insert a voltage source as shown in the lower part of Fig. 11, we may still retain the concept of moving flux. In that case, the voltage source would really be a source of flux, while the resistive part would act as a flux sink. This picture is very satisfactory if we look at the Poynting vector in our system. The Poynting vector would indicate that energy flows into the fields from the battery, and then from the fields into the resistor.(10)

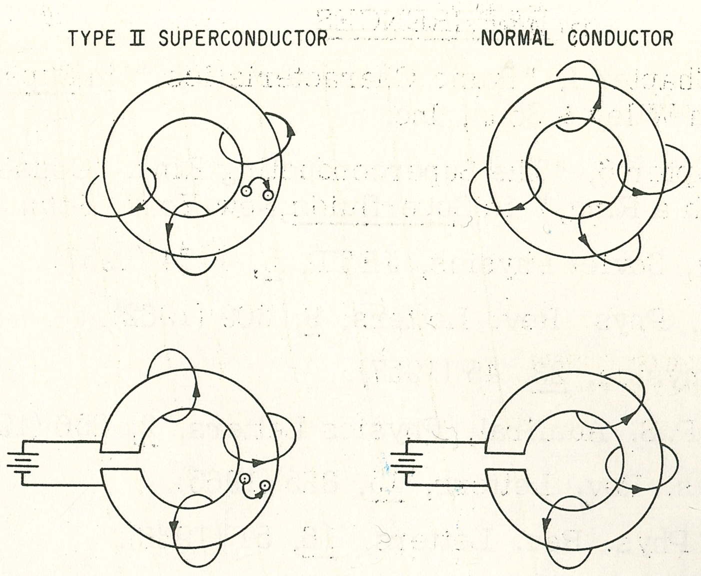

Fig. 11 Two toroids containing flux, i.e., carrying a current. Since the toroid on the left is a type II superconductor, flux may leak out; and the current diminishes. Since the toroid on the right is a normal metal, i.e., resistive, the current will diminish and the flux will "leak out." The end result in both cases is the same, and we could take the point of view of flux flow in a normal conductor as well. The picture of flux flow in the toroids does not change if we insert a battery into the circuit.

We must remember to use extreme caution when we try to develop this and similar physical pictures. As far as anybody knows, Maxwell's equations are always valid; so when physical pictures are used to visualize a situation, it pays to check that the end result is consistent with Maxwell's equation. The simple application of the flux flow concept made above is indeed consistent with Maxwell's equations.

ACKNOWLEDGMENTS

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